Characterizing Signals Using Nonlinear Dynamical Models

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LONG TERM GOALS

Develop new Sonar processing and classification methods based on direct estimation of nonlinear dynamical models from scalar signals. This method has the possibility of exploiting both linear and nonlinear signal correlations, as well as deterministic causal information. The goal is to develop numerically efficient, robust classifiers with significantly improved performance for Sonar transients, broadband, and VLF signatures, which can be implemented on existing Navy processing platforms.

OBJECTIVES

The principal objectives are:

a) Theoretical analysis of simple dynamical models (e.g. DDEs) to determine their modeling properties, and hence their relevance for representing waveforms of sufficient complexity to be of use as new Sonar processing tools.

b) integration of the dynamical model estimation procedure into a classification processing chain, with a consistent definition of a feature space and statistical hypothesis estimators.

c) preliminary evaluation of this processing chain on real data sets supplied by Navy research groups, with a preliminary performance estimate in comparison to existing detection/classification methods.

d) development of a standardized algorithmic implementation (e.g. Matlab) of the processing chain with a user-friendly interface, capable of being ported to Navy facilities for demonstration or second-party analysis purposes.

APPROACH

In the last program year, we have made enormous progress in developing a new theoretical framework for estimating differential equation models from data (described below). This has allowed us to formulate a much more rigorous process for designing dynamical detectors and classifiers, and implement several known feature discrimination metrics. In short, we have re-formulated the previous 'black box' method for dynamical classifiers into a mathematically exact scheme which is much more in line with conventional classification methods, and should be immediately applicable to data analysis problems of current Navy interest.

The principal theoretical approach we are developing is to postulate a time-domain signal model consisting of a continuous (delayed) differential equation of dynamical form. The hypothesis is that such a model can potentially capture data dependencies which are linear, nonlinear, and/or causal.

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Hence, if appropriate classification features can be defined from an estimated model, this approach has the potential to extract additional signal information which can be used to provide classification performance beyond energy or spectral detectors. Because our model classes are usually rather compact (few free parameters), this approach may also provide a more parsimonious representation of certain signal classes, even when the nonlinear signal content is negligible. It is assumed that the dynamical models will be particularly relevant to broadband, S-type, VLF, and transient signal classes, which are problematic in many applications.

Previously, nearly all known methods for estimation of such dynamical models involved simple least-squares ('black-box') estimation. In the last program year, we have made a theoretical leap, by deriving a technique for expressing the unknown model coefficients as functionals of higher-order cumulants derived directly from the data. This method can be loosely considered as a nonlinear generalization of the Yule-Walker relations. Model estimation now consists of the calculation of a specific set of cumulants (simple sums of particular data kernels in the digital domain), which are then combined to yield the estimated coefficients. This technique provides a number of important advantages: firstly, since the fundamental quantities are simple integrals, exact theoretical properties of the estimated coefficients can be calculated, such as the asymptotic form for certain input data classes. Secondly, the form of the cumulants mathematically demonstrates that the dynamical models capture signal information not available in standard linear methods (such as spectra or Arma models). Thirdly, estimation of the coefficients using cumulants is far faster numerically, and more robust. Fourthly, the cumulant functions themselves can be used to generate classification features. Finally, using all of the above, more exact and parsimonious classifiers can be designed to suit particular data classes. In particular, such models are equally applicable to non-stationary signals with deterministic origin.

A large part of the program effort during the last year has involved theoretical development of the above ideas. However, because of this new framework, we have also been able to investigate and implement several additional methods for feature derivation and discrimination. We have investigated detector and classifier design based on thresholding of the mean of multiple observations for a single feature. We have also implemented and investigated a multi-class, multi-feature classifier based on the generalized Mahalanobis distance, which however still assumes Gaussian-distributed features and is most useful in the low-SNR regime. We have also implemented 'logistic discrimination', which is also multi-class and multi-feature, but makes no explicit Gaussian assumption. Testing of these methods in conjunction with the dynamical models indicates that we can now usually design classifiers with predictable asymptotic performance. However, we have also found that the generalized Mahalanobis distance provides the easiest and most generally applicable approach. In addition, we have been collaborating with the NUWC transient classification group to provide theoretical feature distributions which can be used to test our method in the framework of their new theoretical approach to feature space selection.

In addition to the above results, we have recently identified a new model class based on the Ikeda system, which has very advantageous properties which are different from the polynomial model classes we currently use. This model can generate signals of arbitrarily high dimensionality, in many cases being indistinguishable from noise, however the original model is still readily recovered from the observed data. We feel this model is particularly apt for an active Sonar framework, and we are currently planning to investigate its usefulness to insonify simple targets and extract relevant information about their physical properties.

We would like to point out that, as part of this program effort, we have established or maintained several technical collaborations which have proven to be invaluable. An ongoing collaboration with the NUWC transient classification group (Greineder, Baggenstoss, Luginbuhl) provides great insight into transient classification issues, and should be a source of high quality sea test data in the near future. A recently established collaboration with FOA, Stockholm has proven enormously helpful with general acoustic classification issues and active Sonar issues, and will result in several exchanges of scientific personnel in the coming year. This collaboration has also resulted in a potentially new approach for classifying transients based on global geometric properties, which may prove very robust. Finally, a collaboration with the University of Perugia (Italy) made possible a long-term visit from a statistician, Silvia Golia, who was highly valuable in defining exact methods of feature discrimination and hypothesis testing.

The work described above was performed by the PI (Dr. Jim Kadtke), Dr. Mike Kremliovsky, and Dr. Aron Pentek (post-doc) at the Institute for Pure And Applied Physical Science, University of California, San Diego. Small levels of support were also utilized for two visiting researchers: Dr. John Robinson (FOA) and Ms. Silvia Golia (Perugia).

WORK COMPLETED

During FY98 we have completed the following work:

a) derivation of a new, rigorous method for estimating dynamical models from data.

b) identification of a variety of theoretical properties of dynamical models and their derived features.

c) implementation of several accepted methods of feature discrimination and hypothesis testing, and numerical investigation of their properties.

d) identification of a new model class of dynamical form, and of several possible applications which include an active Sonar framework.

e) identification of a potentially new method for classifying transients based on global geometric properties, in collaboration with FOA.

f) implementation of the above ideas in algorithmic form in an integrated, user-friendly Matlab environment.

TECHNICAL RESULTS

The important technical results obtained during the FY98 program period are summarized below:

a) We have discovered that an analytic method can be defined for estimating nonlinear dynamical models from data, which should have profound affect on their development as detectors/classifiers.

b) The above method has indicated several important theoretical properties of dynamical models, such as the specific form of information incorporated in them that is not captured by conventional signal models, and the ability to define new features derived from specific data cumulants.

c) We have been able to implement a number of rigorous feature discrimination metrics and calculate exact performance numbers for various signal examples, which has indicated to us how to exactly design classifiers.

d) We have implemented a new class of dynamical signal model which has significantly different properties than our previous models, and which appears to be useful for active Sonar applications, and has a clandestine capability.

IMPACT/APPLICATIONS

This work should have an impact on a wide range of acoustic signal processing applications for the Navy. It is equally applicable to passive or active modes, on quasi-stationary or transient signals, and potentially to bio-sonar applications. It is particularly apt for broadband signals of artificial origin.

TRANSITIONS

No significant transitions have occured during the current program year. A transition to a 6.3 transient classification program may be likely within the next program year.

RELATED PROJECTS

This project directly supports the transient acoustic classification project [B3] at NUWC. It is also in indirect support of the 6.1 dynamical modeling program headed by Dr. Shlesinger at ONR. It is potentially in support of the biosonar program at SPAWAR in San Diego [A14].

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PUBLICATIONS

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PATENTS

None in 1998.